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In situ Quantification of the Impact of Episodic Enhanced Turbulent Events in Large Phytoplankton

Dr. Percy L. Donaghay, Dr. Jan Rines, and Dr. James Sullivan
Graduate School of Oceanography
University of Rhode Island
Narragansett RI 02882
phone: (401) 874-6944 email: donaghay@gso.uri.edu
phone: (401) 874-6691 email: jrines@gso.uri.edu
phone: (401) 874-6142 email: jsully@gso.uri.edu

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LONG-TERM GOALS

Our long-term goal is to understand how physical-biological, biological-biological and chemical-biological interactions control the patch structure and ecology of phytoplankton inhabiting coastal shelves, upwelling areas, fjords and banks. We are especially interested in ways in which species-specific properties, including colony size and shape (diatoms) and motility (flagellates and photosynthetic ciliates) interact with physical processes to regulate phytoplankton dynamics and spatial-temporal distribution patterns. We wish to understand these interactions in sufficient detail to be able to predict bloom dynamics, biodiversity, size structure, and the impact of species-specific characteristics of the phytoplankton on ocean optics.

OBJECTIVES

Our short-term objective is to focus on field-testing the techniques needed to quantify *in situ* the effects of episodic enhanced turbulent events on large chain-forming phytoplankton and the bulk optical properties of the fraction of the water column mixed by the event. We are particularly interested in field testing our lab-based models which predict that high turbulence levels (such as those occurring during episodic wind events or flows across sills) will break long chains of fragile diatom species and damage or even kill individual cells of sensitive species thus altering the particle characteristics, size structure, and composition of the phytoplankton community and the resulting bulk optical properties of the water column. We are also interested in testing our lab-based models that predict that chain length and morphology of large chain forming diatoms are sensitive to low to moderate levels of turbulence during bloom development.

APPROACH

Our approach during this grant was to conduct field experiments designed to test the *in situ* scanning flow cytometry and autonomous profiling techniques needed to quantify the effects of episodic enhanced turbulent events on large non-spheroid phytoplankton and the bulk inherent optical properties of the water column. Our approach had four components. First, we conducted these experiments in East Sound, WA, (a 2 by 12 km by 30 m deep fjord) where topography constrains

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lateral advection thus allowing the autonomous moored profilers and small boats to repeatedly sample the populations of large chain forming diatoms that develop layered (not necessarily thin) blooms that frequently develop in this system between turbulent mixing events. Second, we deployed one of our ORCAS autonomous moored profilers equipped with a Nortek Vector velocimeter in the upper East Sound and used it to collect the time series of hourly fine-scale profiles need to (1) quantify temporal changes in the abundance, bio-optical characteristics and fine-scale vertical structure of phytoplankton, (2) quantify the exposure of these phytoplankton to small-scale shear and turbulence before, during and after wind events, and (3) estimate changes during the wind event in the intensity, vertical extent, and persistence of lateral flows in the surface mixed layer and pycnocline. Third, we used our surface-deployed slow descent profiler to measure temporal and spatial variation in fine-scale optical structure of dissolved and particulate material inside East Sound and in adjacent waters. We used the resulting data to (1) quantify the spatial extent of the impact of storms on fine-scale physical, chemical and bio-optical structure, (2) select locations and depths for the collection of discrete water samples, and (3) extend the measurements made by the ORCAS autonomous moored profiler. Fourth, we collected water samples from features of interest for (1) immediate on-board analysis of individual particle characteristics using video microscopy and scanning flow cytometery and (2) post-cruise analysis of species abundance in the lab. We used the video microscope to characterize (a) the composition, size and morphology of the large phytoplankton in each sample, and (b) the presence of dead cells and broken chains. We used CytoSense to measure the side scattering, forward scattering and spectral fluorescence (5 wavelengths) at 0.5 micron intervals along the length of each particle. We used comparisons with the microscopic data to evaluate the ability of our CytoSense submersible scanning flow cytometer to quantify *in situ* not only the abundance, length and bio-optical characteristics of large non-spheroid phytoplankton, but also the occurrence of broken chains and damaged or dead cells.

WORK COMPLETED

Data processing and analysis of profiler data: We have completed the processing and analysis of data from the 2009 and 2010 experiments. We have used time series plots of data from the autonomous profiler to quantify changes in fine-scale physical, chemical and bio-optical structure during and following episodic wind mixing events. We have combined data from the autonomous and ship-deployed profilers and plotted the data as transects along the axis of the sound to look for spatial differences in the impact of wind events on physical, chemical and bio-optical structure. We have compared time series plots of data from selected high-resolution profiler stations to evaluate spatial differences in the evolution if vertical structure in different parts of East Sound.

Analysis of scanning flow cytometery, video-microscopy and cell count data: We have completed counting of the discrete phytoplankton samples collected in the 2009 and 2010 cruises and used the resulting data to evaluate our CytoSense based estimates of changes in the abundance of live and dead cells of large diatom species. We have developed and applied a new algorithm that converts the CytoSense data into plots of any measured property as a function of particle length.

Papers published or in press: We have published one paper and have 2 more in press. The first paper (French-McCay et al, 2010) uses a numerical bio-physical model based on an early tow-tank patch experiment to demonstrate the importance of vertical swimming behavior in controlling lateral dispersal of a patch exposed to current shear. The second paper (Graff et al, in press) uses data collected during our LOCO experiments in Monterey Bay to demonstrate that thin layers of phytoplankton have far fewer attached bacteria than individuals of the same species found outside thin layers. The third paper (Sullivan et al, in press) uses a detailed analysis of approaches to measuring

optical scattering to provide a firm physical and numerical basis for our measurements of optical scattering in the ocean.

RESULTS

Quantifying the impact of episodic enhanced turbulent events on large phytoplankton: A storm on May 11-12, 2010 provided an opportunity to test our approach to quantifying the impact of episodic enhanced turbulent events on large phytoplankton and the optical properties of the water column. This storm generated a strong south wind event that mixed the water column in upper East Sound down to 18 m. Ship-based profiling before and after the event showed that the storm had dispersed the layers of large chain-forming diatoms that had dominated vertical bio-optical structure throughout upper East Sound. Flow-cytometric analysis of samples collected from the upper water column before (Figure 1a) and after (Figure 1b) the storm showed a dramatic reduction in the length of large phytoplankton immediately after the storm (Figure 1b) and a subsequent increase in dead cells over the next few days. Hourly profiles collected during the storm by our ORCAS autonomous moored profiler showed that phytoplankton in near surface waters were exposed more than 6 hours of very high levels of turbulence (turbulent energy dissipation rates of 10^{-4} to 10^{-3} m^2s^{-3}) that were sufficiently high to break chains and kill sensitive species in lab studies. In contrast, phytoplankton in the pycnocline were exposed to much lower levels of turbulence (turbulent energy dissipation rates of about 10^{-7} m^2s^{-3}) that were shown to be optimal for growth and formation of long diatom chains in lab studies. Although the southeast wind event rapidly mixed the surface layer down to 11 m (Figure 2i-j) thus potentially exposing more of the phytoplankton to high surface turbulence, it generated relatively weak currents flowing northwest along the axis of the sound in the surface layer and a weak counter current flowing southeast in the pycnocline (Figure 2e-h). Given this, it is not surprising that we saw the changes in phytoplankton length and mortality noted above. The weakness of these currents is important from a tactical perspective since it simplifies using an array of autonomous profilers and our CytoSense deployed *in situ* to measure the impact of enhanced turbulence events in future experiments.

Quantifying the impact of storms on thin layer dynamics in the pycnocline: Fine-scale data collected by the optical and physical sensors on our autonomous moored profiler showed that thin layers increased in the pycnocline at the same time that the surface layer became well mixed (Figure 3). These thin layers had very different temperature, salinity and optical properties from the surrounding water (Figure 3). For example, a thin phytoplankton layer rapidly developed in the upper pycnocline (Figure 3b) in association with a salinity minimum (dashed black arrow, Figure 3i). This high chlorophyll a, low salinity layer occurred just below a layer of low phytoplankton, but higher salinity and temperature (dashed cyan narrow, Figure 3). These multiple thin layers persisted for 5 hours in both chlorophyll a (Figure 3 b-f) and salinity profiles (Figure 3i-m) before disappearing as currents at these depths shifted more to the east (Figure 2g-f). Our ongoing analysis of the temperature and salinity data is consistent with the hypothesis that these layers are the result of the storm creating lateral density gradients that drove multiple very thin lateral intrusions in the upper pycnocline.

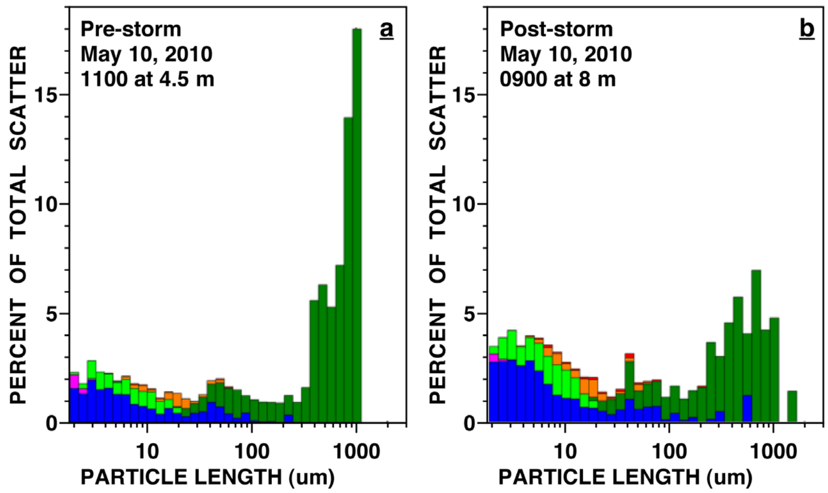

Figure 1: Effect of an episodic wind-mixing event on particle length as measured by the percent of total scattering contributed by particles of different length and bio-optical fluorescence characteristics. Data were collected by our CytoSense scanning flow cytometer on samples collected from the upper water column before (1a) and after (1b) the wind event on May 11-12, 2010. The color codes for the bars are dark green for chlorophyll a containing phytoplankton that are longer than 20 um and and light green for those that are shorter than 20 um, orange for cryptomonads and other phycoerythrin containing plankton, blue for non-pigment containing particles, and purple for cynobacteria. The figure shows that length of long chain forming diatoms (300-1000 um) decreased dramatically following the storm (compare 1a and b).

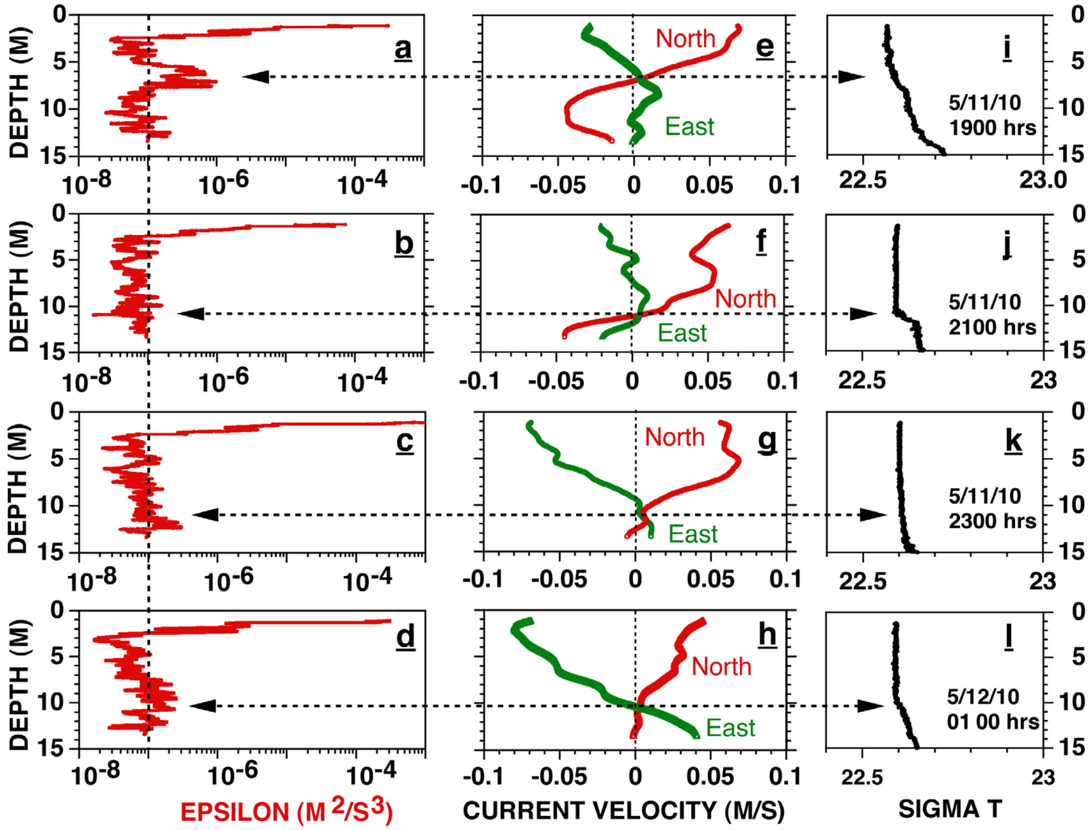

Figure 2. Impact of the south wind event (2i) on May 11-12, 2010 on temporal changes in fine-scale structure of turbulent energy dissipation rate (Epsilon, red line, 2a-d, current velocity (green for east component and red for north component, 2e-h) and density (Sigma t, 2i-l). The black dashed arrow indicates the correspondence between the depth of the bottom of the northwest flowing surface current (2e-h) and features in the fine-scale structure of energy dissipation (2a-d) and density (2i-l). Data for estimating epsilon and currents were collected in upper East Sound by the Sontek ADV on our ORCAS autonomous moored profiler. Figure 2a-d shows that while the storm generated very high (10^{-3} m^2/s^3) turbulent energy dissipation rates in near surface waters (2a-d), energy dissipation rates were 10^3 to 10^5 lower below 3 m. Figure 2e-h shows that while the wind event generated a modest surface currents flowing north and west along the axis of the sound, current velocities declined with depth and changed direction to form a counter current.

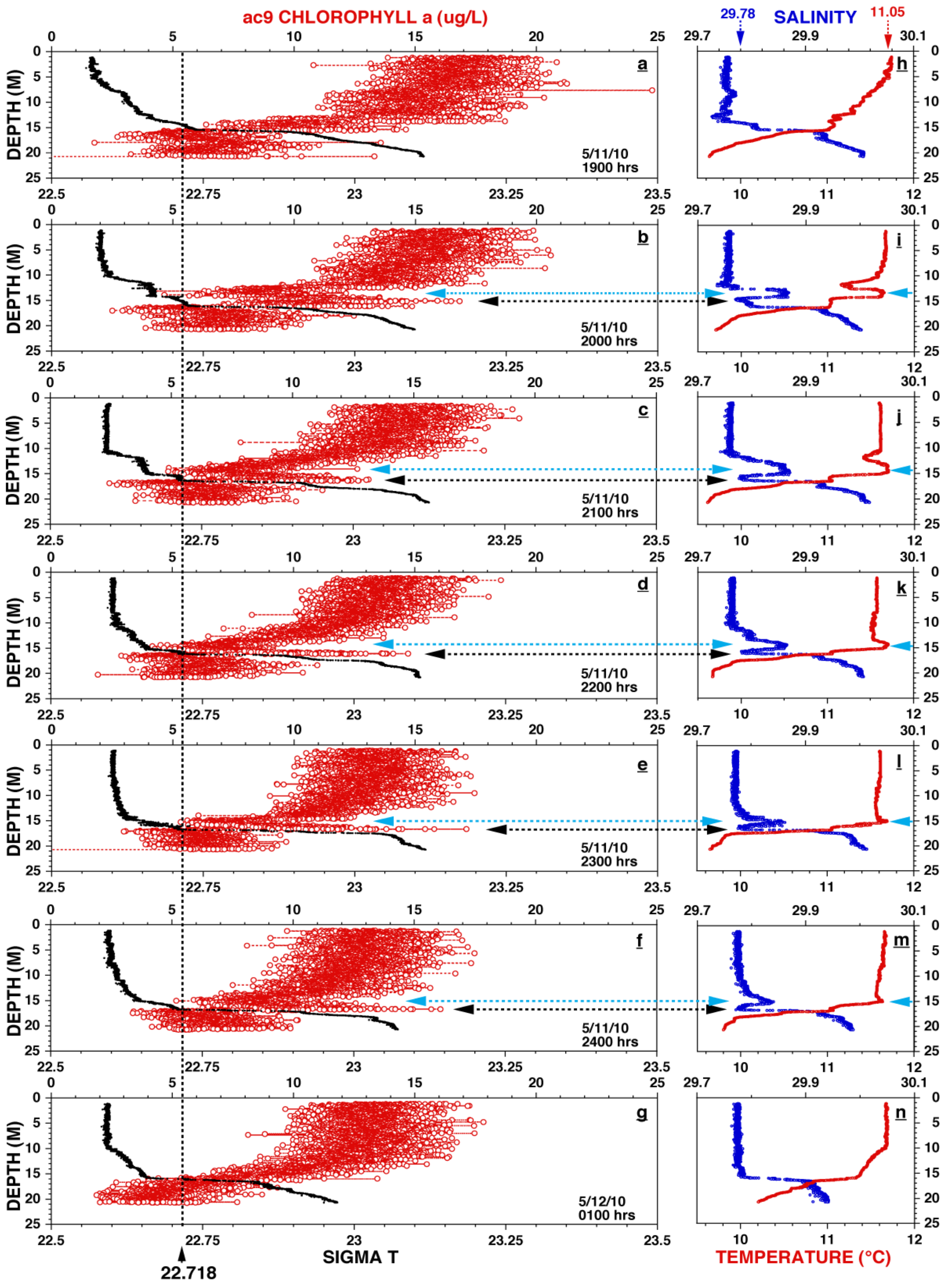

Figure 3. Impact of the south wind event in East Sound on May 11-12, 2010 on the fine-scale structure of phytoplankton biomass (chlorophyll a, red circles, Figure 3a-g), density (black dots, 3a-g), salinity (blue line Figure 3h-n), and temperature (red line, Figure 3h-n). Data were collected by the ORCAS autonomous moored profiler in upper East Sound. The figure shows that while the storm resulted in well-mixed surface layer, a thin phytoplankton layer rapidly developed in the pycnocline in association with a salinity minimum (dashed black arrow) that occurred just below a layer of low phytoplankton, but higher salinity and temperature (dashed cyan narrow).

IMPACT/APPLICATION

This project has several important impacts/applications. First, our field tests have provided critical new evidence for the impact of episodic enhanced turbulent events on large chain-forming phytoplankton. Equally importantly, they have allowed us to refine our approach to the point where we can design and conduct *in situ* tests of our lab-based models by using CytoSense deployed on an ORCAS profiler to measure changes in particle characteristics *in situ* during episodic wind events. Second, our field tests not only have provided critical new evidence for the formation of thin layers in the pycnocline, but they have also provided new insights into the potential importance of very thin lateral intrusions in creating thin layers. Although we have long suspected otherwise, it is now very clear to us that shear is not the only physical mechanism for generating very thin layers. Equally importantly, the discovery that these thin layers have distinctive physical, chemical and bio-optical signatures provides an approach that would allow us to track them in time and space so that we could quantify their impact on lateral mixing and transport. Such a capability could have broad applications in physical, chemical and biological oceanography.

RELATED PROJECTS

This project has been coordinated with our lidar validation project entitled *"In situ* Validation of the Source of Thin Layers Detected by NOAA Airborne Fish Lidar". This lidar project was funded under ONR grant number N000140410276 to Percy L. Donaghay (PI), Jan Rines and James Sullivan at URI and a companion ONR contract number N00014091P20039 to James Churnside (PI) at NOAA. This project has also been coordinated with our NOPP holocamera project entitled " A submersible holographic camera for the undisturbed characterization of optically relevant particles in water (HOLOCAM)". This project was funded with James Sullivan at WET Labs as the lead PI, with subcontracts to Percy Donaghay (PI, URI subcontract) and Joseph Katz (PI, JHU subcontract).

REFERENCES

Donaghay, P.L., and T.R. Osborn, 1997. “Toward a theory of biological-physical control of harmful algal bloom dynamics and impacts,” Limnol. Oceanogr., 42(5): 1283-1296.

French-McCay, D., P. L. Donaghay, R. Campbell, H. M. Rines, and J. E. B. Rines, 2010. "Modeling analysis of physical transport and swimming behaviors determining plankton distributions". Estuarine and Coastal Modeling: Proceedings of the Eleventh International Conference, November 4-6, 2009, Seattle, Washington; Malcolm L Spaulding (editor), American Society of Civil Engineers, Reston, Va., ISBN 9780784411216, 2010, 792p.

Graff, J.R., J. E. B. Rines, and P. L. Donaghay, in press. "Bacterial colonization of phytoplankton in the pelagic marine environment", Marine Ecology Progress Series.

Sullivan, J. M., M. Twardowski, R. Zaneveld and C. Moore, in press. "Measuring optical backscatter in water", Light Scattering Reviews (Vol 7).